Unit power periscopes. (Final Report No. 16.1-70.) Louis G. Henyey, Jesse L. Greenstein and W. A. Hiltner. OEMsr-1078; OSRD No. 4502. Yerkes Observatory. September, 1945.

DIV.16-130-M1

RESTRICTED

Office of Scientific Research and Development

NATIONAL DEFENSE RESEARCH COMMITTEE

Section 16.1 -- Optical Instruments

YERKES OPTICAL BUREAU
Yerkes Observatory
University of Chicago
Williams Bay, Wisconsin

Final Report on
UNIT POWER PERISCOPES
Contract No. OEMsr-1078
September, 1945

Section 16.1 Report No. 70

Copy No. 42

OSRD Report No. 4502

Dr. L. G. Henyey
Technical Representative
Dr. J. L. Greenstein
Dr. W. A. Hiltner

RESTRICTED

Distribution List

of Report on

UNIT POWER PERISCOPES

Copy Addressed to	Copy Number
Office of the Executive Secretary, OSRD	1 - 7
Liaison Office, OSRD	8 - 26
Dean George R. Harrison, Chief, Division 15	27
Section 16.1 Members:	
T. Dunham, Jr., Chief	28
I. S. Bowen	29
W. V. Houston	30
R. R. McMath	31
G. W. Morey	32
F. E. Wright	33
Section 16.1 Contractors:	
Yerkes Observatory (OEMsr-1078)	34 - 35
University of Rochester (OEMsr-160)	36
Liaison Officers - Project NR-111	
Army Air Forces, Material Command, Wright Field, Dayton, Ohio (Lt. H. M. Goldmann)	37
Commanding Officer, ASDevLant, U. S. Naval Air Station, Quonset Point, R. I. (Lt. Comdr. K. E. Wright)	38
Chief of the Bureau of Ordnance (Lt. Philip Nolan)	39
Section 16.1 Files	40 - 75

FOREWORD

This report describes the design of several different types of unit power periscopes which have been developed at the Yerkes Observatory, under Contract OEMsr-1078.

Two 18"-offset periscopes with 40° field diameter have been developed on the basis of an informal request by Lt. Eugene L. Berman of the Signal Corps Photographic Center, Pictorial Engineering Research Laboratory, Long Island City, New York. These periscopes are intended to serve as finders for 35 mm. motion picture cameras when used in fox holes and under other combat conditions requiring periscopic finders. The designs have been turned over to the Signal Corps Photographic Center, with the understanding that this center would have models made.

A 36"-offset periscope with 24° field diameter has been designed, under Project NR-111, for use in Naval aircraft with linkage to other equipment. The design was made as simple as possible, to facilitate production. Four identical cemented doublets are used. The mechanical design of the periscope was developed by ASDevLant, at the U.S. Naval Air Base, Quonset Point, R.I. A prototype of the complete instrument was constructed by Harvard University, under Contract OEMsr-474. The design of the instrument will be described in OSRD Report No. 6022, Section 16.1 Report No. 124, which is being prepared by Harvard. Several models of this instrument, known as Aircraft Periscope Mark 35, were made by the Bureau of Ordnance and were successfully tested under operating conditions.

A telescope 110" in length has been designed to enable the pilot to extend his view 12° below horizontal in the P-51 aircraft. The lenses are approximately 8" in diameter and could be made of plastics. The eye-lens would be fitted into the canopy in such a way as to cause minimum disturbance when the pilot sweeps his vision from looking through the plexiglass to looking through the eyelens of the telescope. This design would be well adapted for installation of opaque reticles linked to lead-computing mechanism. Although several groups expressed considerable interest in this development, it was not covered by a Service request, and time did not permit making a model.

Theodore Dunham, Jr.
Chief, Section 16.1, NDRC
Optical Instruments

Room 7, Grays Hall
Harvard University
Cambridge 38, Mass.
October 23, 1945

INDEX

Introduction

Unit power erecting telescopes have a variety of military applications in which they are used, in effect, to project an observer's eye to a new position more advantageous for observational, operational or safety reasons. They serve as pointing or aiming devices for guns, bomb sights, cameras, etc. Unit power may be used when no higher power is required or is optically attainable, or (more significantly) when higher powers are undesirable for psychological reasons. This latter condition is encountered when apparent angular sizes and distances must be kept at their natural level, for correlation with muscular reflexes. The following Report is devoted to a discussion of several such instruments designed at the Yerkes Observatory.

General Optical Principles

A lens-erecting telescope consists essentially of two inverting or astronomical telescopes set end to end. Let the two halves be identical and set them as follows. If the light traverses the first telescope from lens A to lens B, the second telescope is set in the reverse sense, with light striking lens B first. (The second half is a mirror-image of the first half.) We may call this the symmetric type, and with minor modifications it represents the basic principle of the devices described in this Report. Of course the imagery of the pupil must be carefully controlled by the use of appropriate collective lenses near the real images, to adjust the eye relief and to prevent excessive lens sizes. One property of the symmetric type is that the entrance pupil is as far forward of the objective as the exit pupil is behind the eyelens.

Symmetry may be carried one step further by making each half-system symmetrical about the focal plane. In this way a very satisfactory solution of the problem is obtained by the use of four identical doublets, together with two identical collective lenses. In the symmetrical types, aberrations that vary as an odd power of the field are found to cancel. These include lateral color, coma and distortion. The other aberrations that must be controlled include longitudinal color and spherical aberration, as well as the field aberrations, namely astigmatism, field curvature, and off-axis spherical aberration. These latter are particularly serious because of the large fields usually required in military optics.

Representation of the Aberrations

The aberrations, derived by ray tracing and given in tables for each device considered, represent their optical performance. A perfect telescope would be one in which rays of light, parallel before entering, also emerge as parallel.

Aberrations are measured by the deviations of the directions of the individual rays from a standard direction appropriate to the bundle. This we take as the emergent direction of the principal ray, which is the ray passing through the center of the entrance pupil. The different rays at a given field angle are distinguished by the point at which they traverse the entrance pupil.

A considerable part of the deviation from parallelism, particularly in the outer portions of the field, arises from the curvature of the field. This effect produces angular deviations which are very nearly proportional to the radius of the zone at which the rays traverse the entrance pupil. Superimposed are other deviations of a more irregular character, arising from other aberrations. Since the youthful eye can accommodate itself to considerable amounts of the curvature effect, while it perceives other aberrations as a direct blurring, it appears desirable to separate the two. Accordingly the aberration tables given below give the accommodation (designated as Acc.) in diopters, separately at each part of the field. For judging these values, note that the average range of accommodation of healthy eyes varies from 11 diopters at age 20 to 8 diopters at age 32; some strain may be experienced if the eye is working near the limits of accommodation.

After correcting for the effects of curvature the remaining deviations from parallelism give the optical defects or aberrations. In order to get a complete picture of these defects it may be thought ray tracing should be carried out for rays distributed uniformly over the entrance pupil. However experience has shown that, except for astigmatism, the largest effects are found for rays lying in the principal section -- the section formed by the plane containing the principal ray and the optical axis. These rays we distinguish by the height, a , at which they strike the entrance pupil. Their deviations from parallelism with the principal ray, after correcting for the curvature, may be found in the aberration tables, expressed in mils. The effect of astigmatism in the secondary section (perpendicular to the primary) has been obtained by subsidiary computations. The tabulated quantity, labelled Sec, represents the effects over the entire pupil, across its secondary section, of the astigmatism and the accommodation adopted at that field. The choice of accommodation is such that the aberrations are a minimum; this involves accommodation to what is usually called the "surface of least confusion." Since the Sec is proportional to the pupil, the aberration may be estimated at any desired aperture. To the Sec should be added the axial aberrations, which are equal in primary and secondary sections, in order to obtain a more correct notion of the secondary aberrations.

Two other numbers are given. P_e is the estimated maximum angular disk of confusion as seen by the daylight eye,

taken as having aperture 0.1 inch. It is evaluated by taking the aberrations of all the rays through a .1" opening, when that opening is placed so as to give the worst possible circle of confusion. P_o, on the other hand, represents the estimated total extent of the disk of confusion if the eye were large enough to take all the rays. P_o has been estimated on the basis of the primary aberrations, as well as the secondary modified by the addition of the axial values. If an instrument is provided with a reticle, the total parallactic shift, P_{ret}, of an object in the field with respect to the reticle marking, is also given.

The 18" Periscope

The Signal Corps requested a design for a periscopic finder for use with a 35 mm motion picture camera, for photography of combat operations. The purpose was to set the camera and the top prism of the periscope about 18" above the operator's eye level, on a rotatable stand. The normal eye-level finder on the cameras had been found dangerous, while the new scheme would allow the user to remain behind or beneath some obstruction. A real field of 40° diameter, with magnification 1X or 1.5X, was requested, and an exit pupil larger than 4 mm. The two alternative designs submitted are given below. While these have certain differences, they have one optical principle fundamentally in common, relating to the method of correcting astigmatism and longitudinal color. Correction of color, lens by lens, requires the use of cemented doublets placed at some distance from the pupil points (to control astigmatism), or of more complex lens systems. Since some eye relief is needed, and complexity is undesirable, doublets might be expected to provide a solution. Unfortunately the 20° field leads to excessively large angles on the cemented surface of the doublets. The longitudinal color of simple lenses is relatively small, and the lateral color tends to cancel in a symmetrical system. We investigated next the use over the larger part of the telescope of chromatically uncorrected lenses placed at the correct distance from the pupil points. The accumulated color could then be controlled at one conveniently chosen central point. The astigmatism control was obtained through the use of uncemented pairs of positive lenses, whose basic principle is as follows: On the side of the doublet where light is parallel, a flat surface is used; the next surface of that lens is centered on the image of the pupil. After a thin air space the light strikes a surface which satisfies the aplanatic condition. The last surface is also centered on the image of the pupil. Anyone familiar with the details of optical theory will recognize that the astigmatism is roughly zero, surface by surface. In practice a little deviation from the basic scheme is needed to give the best overall performance.

In the design of Type 2 some overcorrection is needed to balance the astigmatism introduced in the erector. It was found that the scheme when carried out with dense barium crown glass did not require the use of a collective. The two designs differ in that Type 1 gives critically good definition while Type 2 sacrifices definition somewhat and gains in simplicity of construction.

The chromatic correction in Type 1 is obtained completely in the small cemented doublet behind the diaphragm, in the middle of the periscope. At this point the light is nearly parallel; the doublet has flat external surfaces, so that it introduces no aberrations. It is made of two glasses of the same index in D light, but different dispersions. By centering the cemented surface on the principal ray, no lateral color is introduced; the cemented surface is made sufficiently steep to correct the longitudinal color of the rest of the system. No monochromatic aberrations need be considered, at least in D light.

In Type 2, the erector lenses are set at the pupil point in the middle of the system. A symmetrical triplet is used, and is sufficiently overcorrected for color, to achromatize the entire periscope. It introduces positive astigmatism, since it is at a pupil point; this astigmatism must be eliminated by designing the objective and eyepiece to introduce negative astigmatism.

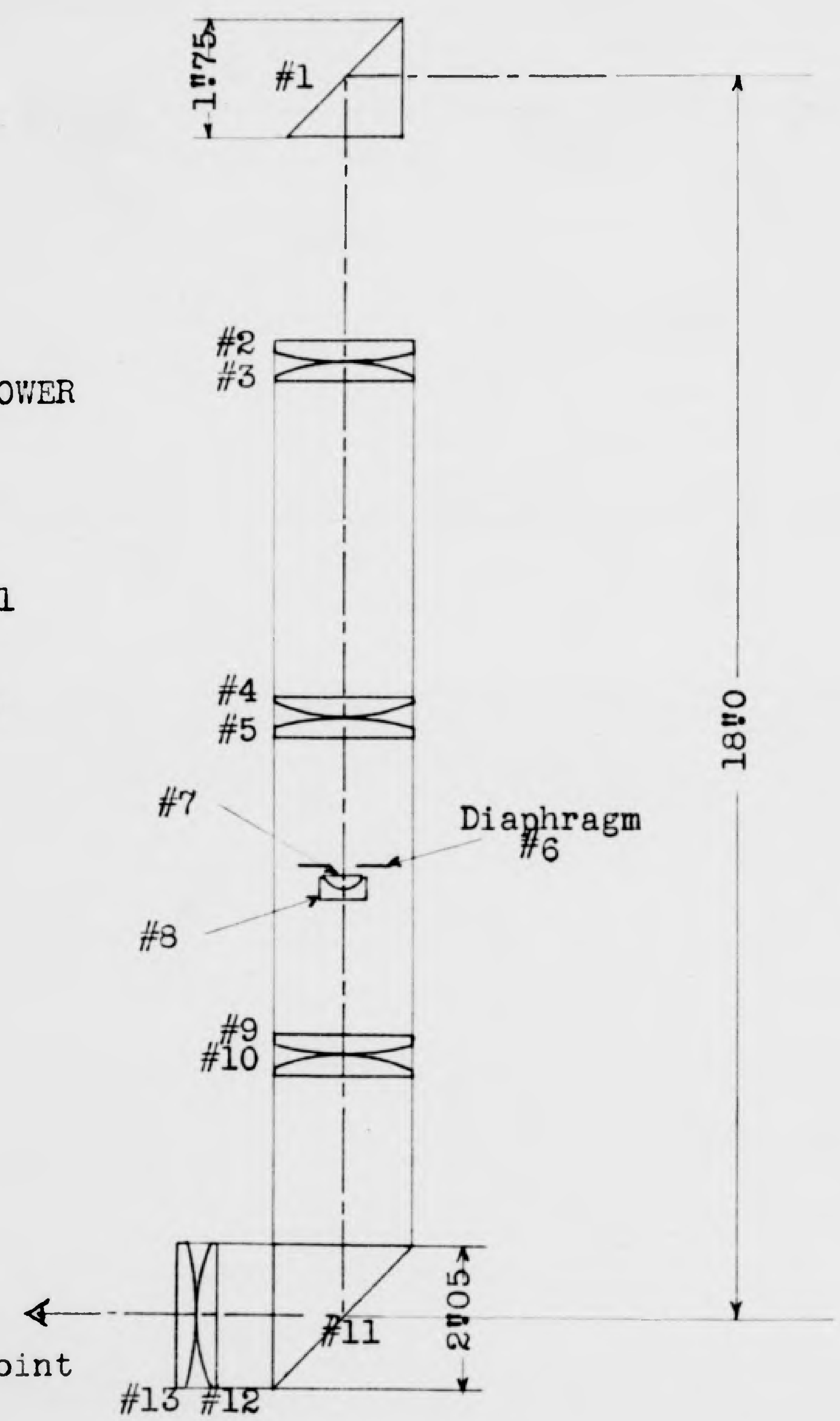
Figure 1

TYPE 1

18" UNIT POWER PERISCOPE

40° Field
10 mm Pupil

SCALE--1/3



Type 1. See Figure 1. This system has a real field of 40° diameter, 10 mm exit pupil and 2.0" eye relief. Table 1 gives the radii, separations and glasses; Table 2 gives the aberrations. This instrument can be used up to 45° field diameter if the lens sizes are increased. If other overall lengths are required, all physical dimensions should be multiplied by the required scale factor. This periscope has excellent definition even at large fields, because of the optical principle involved; the astigmatism is zero at the edge of the field. The axial performance is also of high quality. Higher-order coma, and off-axis spherical are the residual aberrations. Since the instrument is not well corrected for color at its real foci, there is no position where an accurate reticle can be set. No reticle was requested, but if one should be needed, a cross to indicate the center, or lines to show the margins of the camera field, can be set on a reticle at the front focus of the periscope.

Type 2. This periscope is illustrated in Figure 2. The physical data are in Table 3, and the aberrations in Table 4. The field diameter is 40°, exit pupil 7 mm and eye relief 1.6". Simplicity of construction was the goal in this design, and only 7 lenses are used, with smaller diameters than in Type 1. The aberrations are not as highly corrected, but the system should be sufficiently good for its application

Table 1

OPTICAL DATA FOR THE TYPE 1, 18" PERISCOPE

Element	Radius	d	Glass	O.D.
1. 90° Top Prism	Flat			
		1.75"	BSC-2	1.75"
	Flat			
		3.00	air	
	Flat			
2. Objective		0.29	DBC-1	2.05
	-4.04"			
		0.015	air	
	+2.59			
3. Objective		0.29	DBC-1	2.05
	Flat			
		4.60	air	
	Flat			
4. Erector		0.29	DBC-1	2.05
	-2.59			
		0.015	air	
	+4.04			
5. Erector		0.29	DBC-1	2.05
	Flat			
		1.90	air	
6. Diaphragm	--			0.40
		0.06	air	
	Flat			
7.) 8.) Cemented Achromatizer		0.18	DBC-2	0.55
	-0.30			
		0.18	DF-2	0.75
	Flat			
		1.96	air	
	Flat			
9. Erector		0.29	DBC-1	2.05
	-4.04			
		0.015	air	
	+2.59			
10. Erector		0.29	DBC-1	2.05
	Flat			
		2.43	air	
11. 90° Bottom Prism	Flat			
		2.05	BSC-2	2.05
	Flat			
		0.82*	air	
	Flat			
12. Eyepiece		0.29	DBC-1	2.05
	-2.59			
		0.015	air	
	+4.04			
13. Eyepiece		0.29	DBC-1	2.05
	Flat			
		2.00" to eye		

All clear apertures assumed 0.10" less than O.D.; except #7, #8 where 0.05" is assumed. #12 and #13 constitute eyepiece, adjust separation marked with * for focussing.

Table 2

Aberrations, in Mils, of Type 1, 18" Periscope

a	Color	$U_1 = 0°$	$U_1 = 14°$	$U_1 = 20°$
	C	+0.1		
+0.18"	D	+0.2	-0.4	-0.2*
	F	+0.3		
+0.14	D	-0.1		
+0.09	D	-0.1	-0.4	-0.2
0.00	D	0.0	0.0	0.0
-0.09	D	+0.1	0.0	0.0
-0.14	D	+0.1		
	C	-0.1		
-0.18	D	-0.2	-0.9	-1.6*
	F	-0.3		-2.1*
	Sec (Mils)	--	+0.4	-0.5
	Acc (Diopters)	+2.2	+1.2	0.0
	P_e (Mils)	0.4	0.9	0.9
	P_o (Mils)	0.5	1.2	1.5

*Note that there is some vignetting near full field, and the rays marked with an asterisk are vignetted. Transmitted aperture in the primary section is about 0.18" at full field.

as a camera finder. The off-axis spherical aberration is the outstanding defect; if a reticle must be used, it will show chromatic aberration as well. Note that the top prism, which is in an exposed position, has been kept as small as possible; if danger of breakage exists, it may be set in a replaceable cap.

The 36" Periscope

A unit-power periscope was requested for use in Navy aircraft. In use, the periscope is linked to other apparatus. The requirements were: - 24^{o} field diameter, large exit pupil and eye relief, and an offset of 36" between the lines of sight. The characteristic design feature of this device involves the use of cemented doublets placed at sufficient distances from the pupil points to control the astigmatism. By proper choice of glasses, for a given eye relief and focal length, a cemented doublet may be designed to give zero or negative astigmatism. This can be accomplished once the focal length, and acceptable eye relief is shown. In general, we find that cemented doublets up to an overall focal ratio of f/2 can be used (the axial focal ratio being, of course, considerably slower). For a given length of tube one can design relatively wide field instruments with small exit pupils, or by sacrifice of field, obtain larger exit pupils. The axial focal ratio, and consequently the entrance pupil

Figure 2

TYPE 2

18" UNIT POWER PERISCOPE

40^{o} Field
7 mm Pupil

SCALE -- 1/3

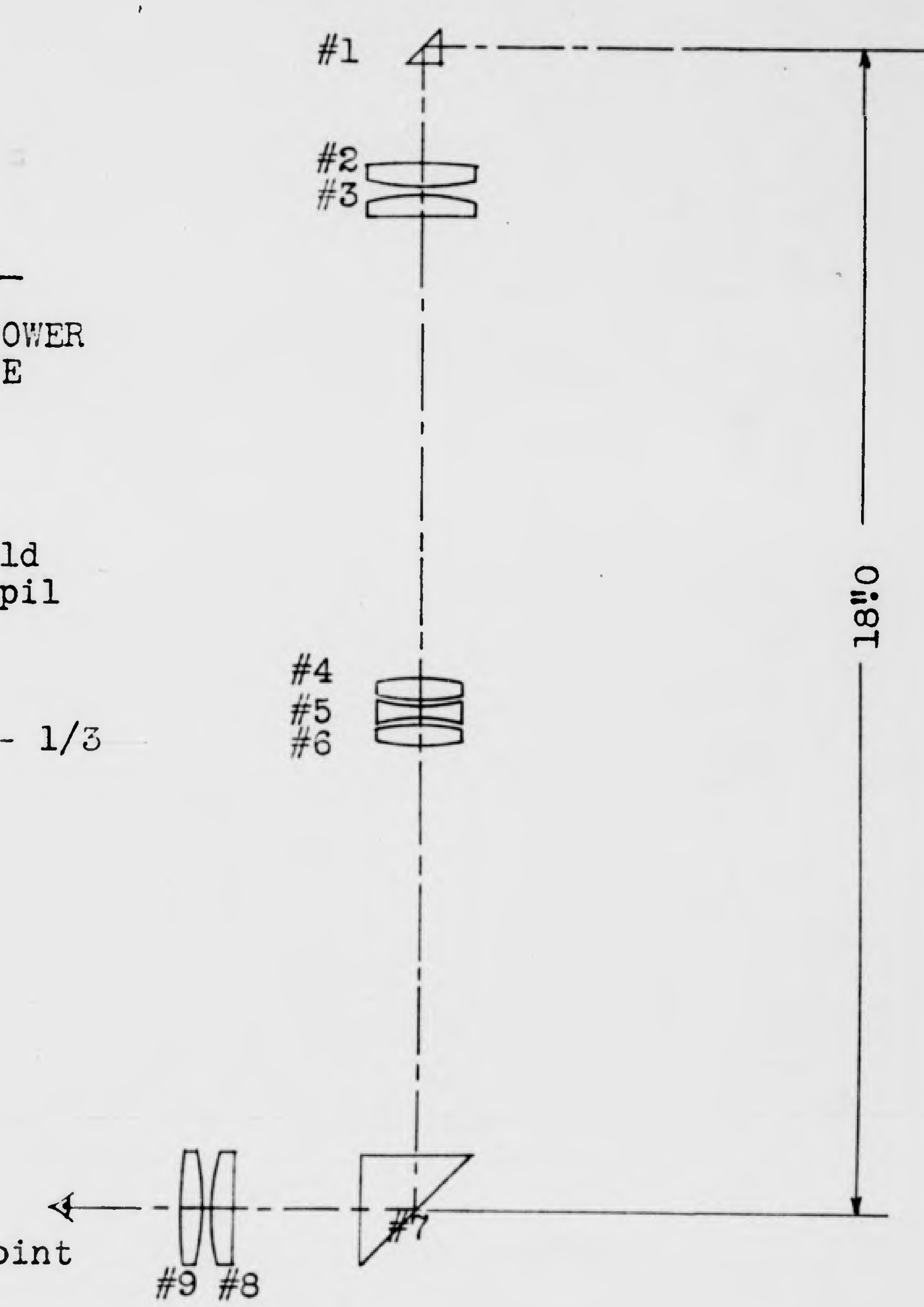


Table 3

OPTICAL DATA FOR THE TYPE 2, 18" PERISCOPE

Element	Radius	d	Glass	D
1. 90° Top Prism	Flat			
		0.50"	BSC-2	0.50"
	Flat			
		1.40	air	
	+7.83"			
2. Objective		0.30	DBC-1	1.55
	-2.61			
		0.11	air	
	+1.96			
3. Objective		0.30	DBC-1	1.55
	Flat			
		8.43	air	
	+3.12			
4. Erector		0.30	DBC-1	1.25
	-3.12			
		0.08	air	
	-2.39			
5. Erector		0.16	DF-2	1.25
	+2.39			
		0.08	air	
	+3.12			
6. Erector		0.30	DBC-1	1.25
	-3.12			
		5.63	air	
7. 90° Bottom Prism	Flat			
		1.50	BSC-2	1.50
	Flat			
		1.81*	air	
	Flat			
8. Eyelens		0.30	DBC-1	1.55
	-1.96			
		0.11	air	
	+2.61			
9. Eyelens		0.30	DBC-1	1.55
	-7.83			
		1.6" to eye		

Clear apertures assumed 0.1" less than O.D.

*Separation adjustable for focussing #8 and #9 together as eyepiece.

Table 4

Aberrations, in Mils, of Type 2, 18" Periscope

a	Color	$U_1 = 0°$	$U_1 = 14°$	$U_1 = 20°$
+0.135"	C D F	-0.9 -0.4 -0.5	-1.2	-0.7
+0.067	D	+0.2	+0.3	+1.3
0.0	D	0.0	0.0	0.0
-0.067	D	-0.2	+0.3	-1.7
-0.135	C D F	+0.9 +0.4 +0.5	+1.8	+2.4
	Sec (Mils)	--	+3.0	+0.2
	Acc (Diopters)	+2.4	+1.0	0.0
	P_e (Mils)	1.5	1.5	2.7
	P_o (Mils)	1.8	2.8	3.9

diameter is set by the permissible level of spherical aberration over the pupil. The size of the pupil is fixed by placing a diaphragm at the midpoint of the system, between the two erectors.

The upper prism of the 36" periscope was made large enough to permit scanning in elevation; the rotation of the instrument permits scanning in azimuth. Mechanical specifications were not rigidly set in advance. The final design shown in Figure 3 gives excellent definition over the entire field. The exit pupil is 0.8" in diameter (20 mm), and the eye relief 4". Ten lenses were used, with maximum diameter 2.5". This design, our Type S4, was built as shown, and also in trial straight telescope form. After tests, a small quantity were built; production of the lenses was found simple, since the tolerances are quite loose. The optical principle adopted, that of complete symmetry, permitted very rapid design and construction.

The design contains four identical cemented doublets and two identical collectives. The glass types used, BSC-2 and EDF-1, are common and easily available; this pair of glasses and the desired eye relief permitted us to obtain some negative astigmatism in the doublets, in the presence of tolerably small spherical aberration. The collectives gave some positive astigmatism. A reticle was to be used, containing both radial line and concentric circle markings, to be

seen black against a bright background. It was possible to design the collective so that its rear surface on which the reticle marks were set had the best radius to fit the image at that point. Consequently objects are sharply imaged on the reticle marks at all fields; object and reticle are then both viewed in identical fashion through the rear part of the telescope.

Table 5 gives the physical data of the system, Type S4, and Table 6 contains the aberrations. Note that the quantity P_{ret} which measures the relative parallax of target and reticle mark, as the eye crosses the entire pupil, is small; this insures that the accuracy of aim will be high. The off-axis spherical aberration is the outstanding residual image defect. It is larger in the primary direction than in the secondary, and tends to flatten the primary field curvature. The best mean field curvature, that to which the eye will accommodate, is thus reduced to only 0.3 diopters, at the edge of the field. At full field there is considerable difference between primary and secondary field curvatures, but in view of the relatively small part of the exit pupil, and consequently of the aberration disk that the eye will straddle, there is small effect on the sharpness of the image. P_e is always small; the effect of the field curvatures is to make P_o appreciable. However, this aberration results only in an apparent shift of the direction of both target and

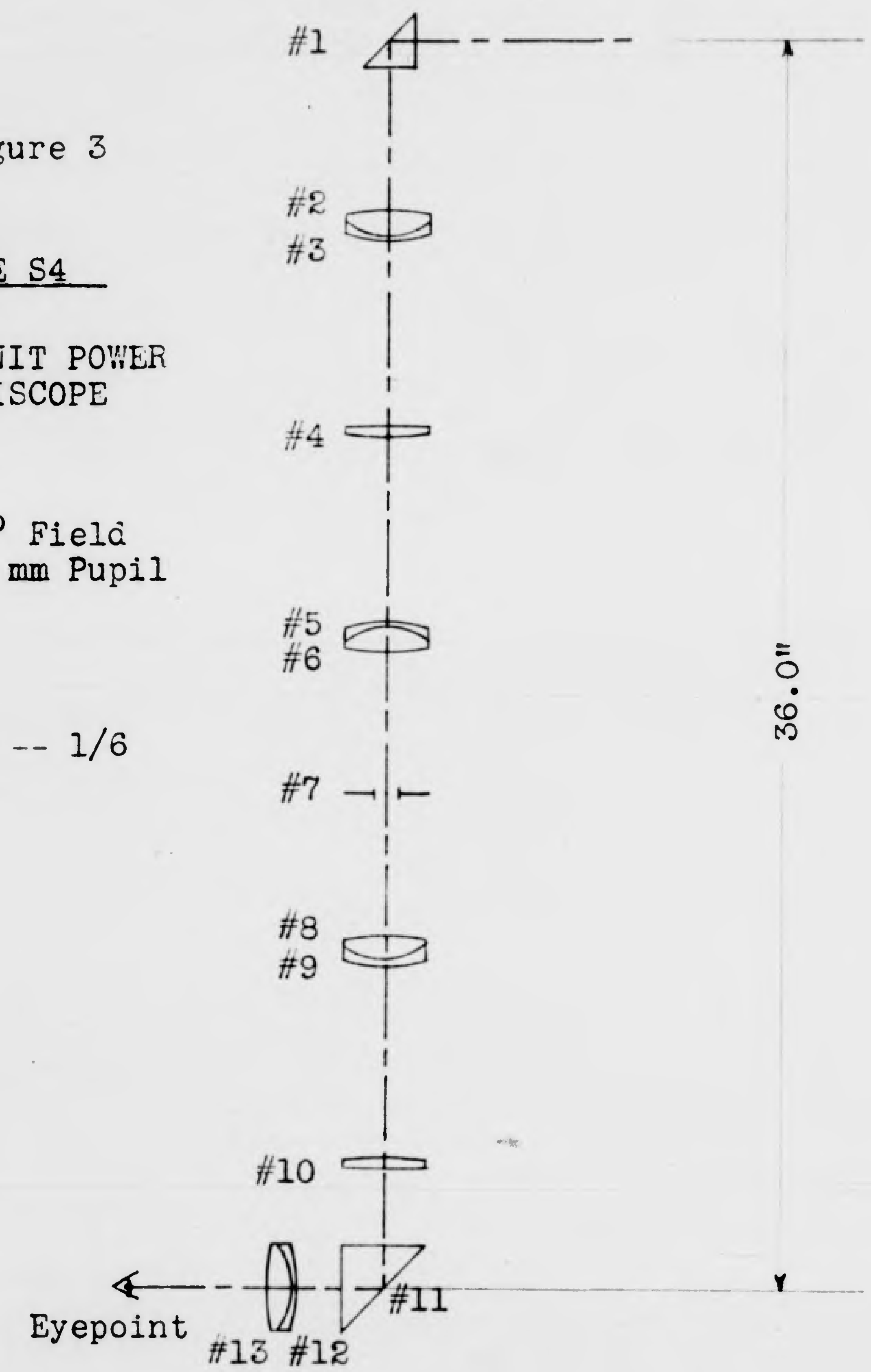


Figure 3

TYPE S4

36" UNIT POWER PERISCOPE

24° Field
20 mm Pupil

SCALE -- 1/6

Table 5
Optical Data for the 36" Periscope, Type S4

Element	Radius	d	Glass	Remarks
1. 90° Scanning Prism	Flat			Entrance pupil on lower face.
		1.50"	BSC-2	Prims 1.50" size.
	Flat			
		4.10	air	
	+6.42"			
2.)Cemented Objective		0.71	BSC-2	2.5" o.d., 2 3/8" clear
)	-1.99			All lenses same size.
3.)		0.17	EDF-1	
	-3.96			
		5.29	air	Adjust to focus on reticle.
	+42.0			
4. 1st Collective,		0.35	DBC-1	Scale 1°=0.099" on reticle.
Reticle (rear face)	-11.15			
		5.39	air	
	+3.96			
5.)Cemented 1st Erector		0.17	EDF-1	
)	+1.99			
6.)		0.71	BSC-2	
	-6.42			
		4.10	air	
7. Diaphragm	--			0.8" aperture
		4.10	air	
	+6.42			
8.)Cemented 2nd Erector		0.71	BSC-2	
)	1.99			
9.)		0.17	EDF-1	
	-3.96			
		5.39	air	
	+11.15			
10. 2nd Collective		0.35	DBC-1	No reticle
	-42.0			
		2.29	air	
	Flat			
11. 90° Fixed Prism		2.50	BSC-2	2.5" Prism size.
	Flat			
		1.35	air	Adjustable to focus eyelens
	+3.96			Range 0.85" inwards.
12)Cemented Eyepiece		0.17	EDF-1	Movement 0.85" per diopter.
)	+1.99			
13.)		0.71	BSC-2	
	-6.42			
		4.1" eye relief		

reticle together, as the eye moves across the exit pupil.

An alternate design, Type S5, exists in which the front collective is separated from the reticle. This may be advantageous in certain applications. A curved glass reticle, which may be substituted with different markings for different applications, is provided. Its effect on the imagery is negligible, and the aberrations are essentially those given for Type S4. No change in the general design of the periscope is required; prisms, objective, erectors and eyepiece are the same. The data in Table 7 are given only for those elements which differ from the Type S4.

Long Unit-Power Telescopes

In 1943 it was suggested that the visibility from the cockpit of the P51b fighter plane needed improvement, especially in the downwards direction. During landing, and during some combat manoeuvers, the pilot's vision was blocked by the forward projection of the nose of the plane. The Mount Wilson group discussed the problem with the aircraft engineers, who felt that it was possible to streamline a long telescope into the upper surface of the nose of the plane, setting the eyepiece just behind the windscreen and above the instrument board. The result of such a telescope would be that the pilot's eye would effectively be set at the entrance pupil of the telescope, i.e. as far forward as desired; if the telescope had a wide

Table 6
Aberrations in Mils of 36" Periscope, Type S4

a	Color	$U_1=0^o$	$U_1=6^o$	$U_1=12^o$
	C	+0.0		
+0.4"	D	+0.4	+0.2	-2.9*
	F	+0.5		
+0.2	D	-0.4	-0.2	-0.2
0.0	D	0.0	0.0	0.0
-0.2	D	+0.4	+0.2	+0.2
	C	-0.0		
-0.4	D	-0.4	-0.2	+3.3*
	F	-0.5		
	Sec (Mils)	--	-1.5	+3.1
	Acc (Diopters)	0.3	0.2	0.0
	P_e (Mils)	0.7	0.6	1.1
	P_o (Mils)	0.7	0.6	6.5
	P_{ret} (Mils)	0.3	0.5	1.7

* Note that these rays are vignetted at full field.

Table 7
Optical Data for the 36" Periscope with separate Reticle, Type S5

Note:- This telescope has certain changes from the Type S4; all entries are the same as in Table 5, except those given below.

Element	Radius	d	Glass	Remarks
3. Objective	-3.96"			This and preceding as in Table 5.
		5.05	air	
	+9.01			
4a. Collective		0.20	DBC 1	
	Flat			
		0.26	air	Adjust to focus reticle.
	-9.01			
4b. Reticle		0.10	BSC-2	Reticle marks on rear.
	-9.01			
		5.42	air	
5. 1st Erector	+3.96			This and following as in Table 5
	....			
9. 2nd Erector	-3.96			
		5.74	air	
	Flat			
10. 2nd Collective		0.20	DBC-1	
	-9.01			
		2.06	air	
11. Fixed Prism	Flat			Following as in Table 5

field, the pilot's downwards vision would be much increased. Magnification was psychologically undesirable, so unit power was adopted. Further conditions were (1) no obstruction of the pilot's vision (2) very large eye relief and exit pupil, to give complete freedom of motion of head and body during use.

From a schematic layout of the nose of the P51b, it appeared that the pilot could normally see only about 3.5° downwards below the fuselage reference plane. If a telescope 84" long, from entrance to exit pupil, is used, the layout shows that the clear downwards vision is increased to 13°, and a telescope 115" long would give about 25°. Telescopes are limited by optical consideration in true field to about 20° radius; but could give larger downwards visibility if the entire telescope is tipped. The telescope may also be somewhat more easily fitted into the streamlining if tipped. A field diameter of 24° is a minimum requirement; also exit pupils of 2.5", and exit pupil distance of 12". The pilot's eyes would be set well behind the exit pupil in use. The pilot's head could move about 4.7" sideways across such a pupil, with one eye still inside the pupil. The telescope obstructs forward vision only over a small range of directions, depending on the thickness of the mounting cells. The pilot can look forward without the telescope by shifting his head sideways (this is necessary because of the possibility of the lenses being destroyed in combat). Minimum size of the eyelens is about 7.5".

The general scale of the lenses used, and the difficulty of a vibration-free mounting on the plane for so long a tube, are serious drawbacks. Some possible advantages of such a telescope may be listed:

(1) Increased visibility in landing and combat.

(2) Reticle marks for computing or lead-estimating sights, up to 400 m.p.h., may be set in the field of view. If the marks are opague, they will be visible against sky over a very wide range of brightness. Suitable night illumination can be provided.

(3) Large eye-relief and large pupil give the pilot greater freedom during combat than is obtained with the usual small reflex-sights or lead-computing sights.

(4) A semi-reflecting, nearly transparent mirror may be set inside the telescope to reflect, with good definition, the dials of flight instruments, or a radar screen, into the line of sight. The pilot could see any necessary instruments during combat, without looking downward at the usual instrument board.

Various optical designs for such long unit-power telescopes were obtained in complete form. If optical plastic materials are acceptable under the conditions of temperature and vibration of a plane, they might conceivably be an economical material for the large lenses required. The P5 telescope design was completed using doublets of CHM-methacrylate and styrene. The length is 113" between lenses, and

Table 8

Optical Data fo the 135" Periscope, Type P5

Element	Radius	d	Plastic	Remarks
	+21.19"			
1. Cemented Objective		1.85"	CHM	7.8" o.d.
	-6.20			
2.		0.40	Styrene	
	-13.05			
		16.08	air	
	+9.63			
3. Collective		0.61	Styrene	7.4" o.d.
	+28.91			
		1.08	air	Focus on reticle
	-16.0			
4. Reticle		0.25	CHM	7.4" o.d.
	-16.0			
		24.11	air	
	+21.05			
5. Cemented 1st Erector		0.40	Styrene	7.3" o.d.
	+7.48			
6.		1.40	CHM	
	-21.05			
		10.2	air	
7. Diaphragm	--			4.37" aperture
		10.2	air	
	+21.05			
8. Cemented 2nd Erector		1.40	CHM	7.3" o.d.
	-7.48			
9.		0.40	Styrene	
	-21.05			
		25.36	air	
	-28.91			
10. 2nd Collective		0.61	Styrene	7.4" o.d.
	-9.63			
		16.08	air	Adjust to focus
	+13.05			
11. Cemented Eyepiece		0.40	Styrene	7.8" o.d.
	+6.20			
12.		1.85	CHM	
	-21.19			
		11.5" to exit pupil		

Note:- It is necessary to cement these doublets.

Table 9

Aberrations of the P5 Plastic Telescope, in Mils

a	Color	$U_1 = 0^o$	$U_1 = 6^o$	$U_1 = 12^o$
	C	+0.5		
+1.5"	D	+0.3	+0.4	+0.6
	F	+0.8		+0.0
+0.75	D	-0.2	-0.2	+0.4
0.0	D	0.0	0.0	0.0
-0.75	D	+0.2	-0.1	-0.1
	C	-0.5		
-1.5"	D	-0.3	-0.6	-0.4
	F	-0.8		
Sec (Mils)		--	-2.0	-2.3
Acc (Diopters)		0.20	0.15	0.00
P_e (Mils)		0.3	0.3	0.3
P_o (Mils)		0.5	1.0	1.0
P_{ret} (Mils)		0.3	0.5	0.5

135" between entrance and exit pupils. Field is 24° diameter, exit pupil 3", eye relief 11". Ten lenses and a curved reticle are used, with apertures from 7.3" to 7.8". Table 8 gives the data, and Table 9 the aberrations of the system. The optical design is partly a symmetrical one. The individual inverting telescopes are not unit power; the first has magnification -2/3X and the second -3/2X. The symmetry conditions are still satisfied. The optical performance of P5 is extremely good; the off-axis spherical aberration is smaller than in the Type S4 (36") periscope. Since off-axis spherical aberration is a difficult aberration to control, the possible usefulness of the plastic achromatic doublet may be worth investigation in wide-field telescopes. We have investigated only one system in plastics, and can make no general statement; nevertheless the improvement in off-axis spherical aberration is large, as can be seen by a comparison of Table 6 and Table 9, at full field.

Division 7 of the NDRC recently suggested the use of moving reticles in a long telescope in fighter aircraft. This unit power device required a clear field of 30° diameter, and a length of 115" from entrance to exit pupil. Since there was no time for a new design, we suggested what is essentially a scaled version of the S4 symmetrical type. The latter was 42" long with the prisms removed. By multiplying all lengths by 2.74X in type S4 we can obtain the data for the Type P6,

given in Table 10. Certain additional changes in size of lenses were made, especially in the collectives, to transmit the larger field required; the diaphragm was also made larger to give more exit pupil. The aberrations are essentially identical with those of S4 (at properly scaled apertures on the pupil), except that they are even smaller across the pupil of the observer's eye; less eye accommodation is required. In this scaling we assumed that reticle marks up to 12° field radius only would be required; if marks are to be used to the edge of the field, the parallactic shifts of the target on the reticle will become larger.

Non-Symmetrical Systems

If we abandon the requirement of symmetry in unit-power telescopes, it might be hoped that the size of at least the front part of these telescopes could be reduced. The size of the lenses is set by the required entrance pupil (equal to the exit pupil in unit power systems) and by the eye relief. If the eye relief is to be kept large, the eyepiece, and the second collective must be large. However, the objectives can be reduced. Such non-symmetrical types require non-unit power erector systems, and in general all the lenses in the telescope will be different from each other, slightly complicating production.

We investigated the possibilities of a unit power

Table 10

Optical Data for the 115" Long Telescope, type P6

Element	Radius	d	Glass	Remarks
	+17.6"			7.25" o.d. 7" clear
1.)		1.95"	BSC-2	
Cemented Objective	-5.45			
2.)		0.47	EDF-1	
	-10.8			
		14.5	air	adjust to focus on reticle.
	+115.			
3. Collective and reticle.		0.96	DBC-1	8.25" o.d. Reticle on rear surface. Scale 0.271" = 1°.
	-30.6			
		14.8	air	
	+10.8			
4.)		0.47	EDF-1	7.25" o.d.
Cemented 1st erector	+5.45			
5.)		1.95	BSC-2	
	-17.6			
		11.2	air	
6. Diaphragm	--			2.5" aperture
		11.2	air	
	+17.6			
7.)		1.95	BSC-2	7.25" o.d.
Cemented 2nd erector	-5.45			
8.)		0.47	EDF-1	
	-10.8			
		14.8	air	
	+30.6			
9. 2nd Collective		0.96	DBC-1	8.25" o.d.
	-115			
		14.5	air	Adjust to focus eyepiece
	+10.8			
10.)		0.47	EDF-1	7.25" o.d.
Cemented eyepiece	+5.45			
11.)		1.95	BSC-2	
	-17.6			
		11.2	air, to exit pupil	

Notes:- The doublets are such that they must be cemented, and some cementing technique suitable for lenses of this size must be developed. The same cemented doublet occurs four times in the design. If the reticle must be separated from the collective, this can be done without essentially altering the system. A reticle of radius -30.6" should be used, set about 0.2" behind the first collective. The objective is then to be focussed on this reticle by reducing the separation between #2 and #3, by approximately this amount.

telescope of 24" field diameter, 72" length, 3" pupil, and 11" eye relief. We also required that the vignetting of the pupil be small, and that the objective be kept as small as possible. We found that the objective had to be at least a quartet, with lenses ranging from 3" to 5" in diameter; the collective was 5", erectors 5" and 6", and the rear collective and eyepiece 8", as before. The reduction in size of the front part of the telescope involves at least two additional lenses. No final design was attained, since none was definitely requested.

Placing of the Reticle

If wide-field telescopes are used with reticle markings that may reach 12° or even 20° off-axis, it must be remembered that the field of a simple telescope is not flat. If a flat reticle is used, care must be taken to insure that the curvature of the target field does not introduce excessive parallactic shifts of the target with respect to the reticle markings as the eye crosses the exit pupil, with consequent inaccuracy of aim. If special objectives (triplets or more complex types) are used, a relatively flat field may be attained. If simple doublets are to be used, the natural field curvature may become appreciable. Curved reticles may then be used, whose radius is that of the surface of least confusion of the system, computed at the point where the reticle is placed. Two real foci are available and the field curvature is less steep if the reticle is set at the first focus, i.e. behind the objective. In a symmetrical system of unit power, without collective lenses, the curvature of the field is one-third as steep, behind the objective, as it is just before the eyelens. The collectives serve to make the reticle steeper, if it is set before the eyelens. In a rough way we can estimate the radius of curvature of the reticle (if astigmatism is absent), at the first focus, as about one-quarter the total length of the system; its radius will be about one-twelfth of the length of the system, if placed just before the eyepiece. Clearly, it is desirable to set reticles at the first focus, if mechanically possible.

As a result of these approximate computations, we can also give an estimate of the eye accommodation, in diopters, required after the eyepiece in a symmetrical unit power telescope using ordinary glasses, of given length and field. Let the length (from entrance to exit pupil) in meters be L; let the field radius be U_1 in degrees. Then the range of eye accommodation between full field and zero field is given approximately in diopters, by

$$\frac{0.0027\, U_1^2}{L} = \text{Diopters Accommodation.}$$

YERKES OPTICAL BUREAU, OEMsr-1078
YERKES OBSERVATORY
Williams Bay, Wisc.

Sept. 1945

APPENDIX

The attached set of curves represents in more detail the data on the ray aberrations included in our Tables for the unit-power periscopes. For each system three curves are given, at field angles U_1. The aberrations from the principal ray are plotted, in mils, as a function of height, a, on the pupil (entrance or exit). All data are for D line aberrations; the secondary curvature is not plotted. We have made the full pupil in each instrument have the same length on the curves, from left to right. For scale, we have drawn a heavy line for each instrument, which represents a pupil size of 0.10". Since the daylight eye pupil size is about 0.10", we can use this length to estimate the aberrations effective in producing a disk of confusion for the eye. The units in the vertical direction (the ordinates) are one mil each.

ABERRATIONS
UNIT-POWER PERISCOPES